Senior Thesis

Magma Emplacement Models for the Jurassic Ferrar Dolerite Province, Antarctica

by

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Introduction

This study examines methods to determine magma flow direction(s) during emplacement of the Jurassic Ferrar Dolerite intrusions in Antarctica. A brief description is given of the techniques used to determine magma flow directions in sheet intrusions, and an explanation of how, from these observations, magma sources for dike swarms can be located. I discuss how to apply these types of data to try and determine the magma source for Jurassic sheet intrusions in Antarctica. I will present three different emplacement models for the linear intrusive belt found within the Transantarctic Mountains. The models include a linear zone of intrusions that could be produced by back-arc spreading related to subduction, a single intrusive source, and multiple magma sources. Magma flow directions predicted by these models are discussed. A possible test of these models from intrusion orientations in the Skelton Neve region is examined.

Magma Flow Indicators

Mesoscopic Features

- Fingers and Grooves

At the outcrop, evidence for determining flow sense in dikes can be found by looking at the contacts between the host rock and the dike. Two diagnostic indicators of flow direction have been described by Baer and Reches (1987). Fingers are elongate, wavy irregularities found along the contacts of the dike rock and the host rock (Figure 1). Grooves are the depressions found in between the fingers (Figure 1). The long axes of fingers and grooves lie parallel to the direction of flow, with the closed end of the fingers pointing in the actual direction of flow. In areas where only the host rock is present in outcrop, it may be possible to find groove molds, which are the imprints of fingers that are made in the host rock.

Petrofabric Features

Many of the types of indicators that are useful for determining flow directions in an intrusive body are found in the body's petrofabric. In each of the following sections, I will describe these types of indicators as described by Philpotts and Asher (1994) and additional sources as indicated.

- Imbrication of Phenocrysts

Near the chilled margins of a dike, a shear zone is present where the flowing magma passes by the unmoving margin. If elongated phenocrysts are within this zone of simple shear, they will tend to be rotated such that their long axes lie nearly parallel to the flow direction (Figures 2 and 3). The acute angle between the dike contact and the long axis of the grains will open in the direction of flow. Due to the proximity of the cooler country rock along the dike contacts, these imbricated crystals should provide evidence for early flow directions because they would have cooled more quickly than magma located further from the contacts, and thus had a better chance of preserving initial flow directions. It is possible for magma to change its direction of flow within an intrusion over time. Therefore, unless the magma crystallizes within a short period of time (as it should near the margins), later flow directions might get preserved in late crystallizing magma.

- Broken and Sheared Phenocrysts

Another way to determine flow direction when looking near the margins of a dike is to look for sheared and/or cataclastically elongated phenocrysts (Figures 3 and 4; Philpotts and Asher, 1994; Smith, 1987). Such structures are commonly found in minerals such as plagioclase where cleavage planes are transverse to the length of the crystal. These indicators are common in silicic dikes where the magma is viscous and shear stresses are high so that the crystals can be split and dragged apart (Smith, 1987). Commonly, such cataclastically elongated minerals are 10 to 20 times longer than they are wide (Smith, 1987). Flow direction is represented by the direction in which the phenocryst has been dragged out. Since these deformed phenocrysts are located near dike margins, it is assumed that the phenocrysts crystallized early, and then were subsequently deformed by magma moving in the initial flow direction which was also "frozen" early due to marginal proximity.

- Alignment of Elongated Vesicles and Amygdules

Where dikes are mafic or intermediate in composition, elongated vesicles and/or amygdules may be found (Figure 4). These features would tend to be found near dike contacts where magma flow became impeded and therefore vesicles became stretched out. Flow direction is determined by the alignment of the long axes of these vesicles which can be up to 7cm long and have length to width ratios of 10 to 1. Vesicles and amygdules will also commonly be found flattened in the plane of the dike. It should be noted that these features would probably not be found where dikes had a deep origin of emplacement where confining pressure was high and a low volatile content would prevent formation of vesicles.

Prismatic minerals such as amphibole have been found aligned with their long axes oriented parallel to the long axes of elongated vesicles (Smith, 1987). By this association, it is therefore assumed that the orientation of the long axes in prismatic crystals is parallel to the flow direction of the magma.

Microscopic Features

- Early Felsic Streaks

As magma flows through a dike, some of the host rock may melt and subsequently expand and force itself into the magma. This host rock fluid remains separate from the magma, crystallizes, and is drawn out into fine wisps by the movement of the magma past the point of intrusion (Figure 3). If left undisturbed by later processes, these wisps will be straight and extend into the dike rock at a slight angle from the contact wall, pointing in the direction of flow. Again, proximity to the contact and assumed rapid crystallization makes this an early flow indicator. If however, folded wisps are found, it is possible that the flowing magma changed directions while the material was still fluid and thus deformed the originally straight wisps.

- Felsic Segregations Attached to Phenocrysts

Where phenocrysts are located within a few centimeters of the dike contact, concentrations of K-rich granophyre may be found attached to the sides of the crystal (Figure 3). These concentrations are drawn out by the flowing magma, and have an asymmetry that can be used to determine flow sense. Any further from the margins, and the granophyre is assimilated with the magma and it becomes impossible to differentiate between the two.

- Reidel Shears

During their studies of the Higganum dike in Connecticut in 1994, Philpotts and Asher found thin (<1mm), planar veins of K-rich granophyre (as seen in thin section) extending approximately 1cm into the diabase of the dike body. These veins were spaced just millimeters apart, and made an angle of approximately 20 degrees with the contact. They determined that the veins pointed in the direction of flow. These structures distorted earlier flow structures in a manner that suggested the filling of shear zones of the Reidel type.

- Ramps

As the magma in a dike begins to solidify, it reaches its yield strength and shearing is set up in discrete zones (Figure 3). In the case of Higganum dike, these zones were observed, in thin section, on surfaces perpendicular to the contact and parallel to the flow direction. Dark zones were present that contained few if any large phenocrysts, while increased concentrations of groundmass biotite were found. These zones were found to make angles from 30 to 80 degrees with the contact, with the opening of the acute angle between the zone and the contact indicating flow direction. Ramps likely indicate late stages of flow because the curved structures are found undisturbed by other flow structures.

Other indicators of flow direction have been described by Smith (1987), and are as follows.

- Asymmetric Drag Folds

In dikes where magma was viscous enough for cataclastic elongation of phenocrysts, asymmetrically folded contacts may also be found (Figure 34; Smith, 1987). The axes of these folds are generally aligned perpendicular to flow direction, and fold crests pinch out into long filaments.

- AMS

In dikes where petrofabrics are weak or the rock composing the dike is aphanitic, the anisotropy of magnetic susceptibility (AMS) can be utilized to study subtle fabrics that can provide insight to magmatic flow directions (Ernst and Baragar, 1992). Rocks that display magnetic anisotropy are those whose intensity of magnetization, be it induced or remnant magnetization, depends on the direction of the applied field (Butler, 1992). This direction of magnetization may or may not coincide with the direction of the magnetic field. Butler (1992) describes two types of magnetic anisotropy. In AMS, susceptibility is a function of the direction of the applied field. In anisotropy of remnant magnetization (ARM), acquired remnant magnetization may differ from the direction of the magnetic field at the time of acquisition.

AMS measurements are expressed by comparing the values of magnetic susceptibility in three mutually perpendicular directions. Along these directions are associated axes that define the magnetic susceptibility ellipsoid. The three axes are defined by K_1= max. susceptibility,

K_2= intermediate susceptibility, and K_3= min. susceptibility. Where K_1= K_2= K_3, the ellipsoid defines a sphere. Where $K_1 \approx K_2$ and $K_2 > K_3$, the ellipsoid is oblate (flattened). Finally, where $K_1 > K_2$ and $K_2 \approx K_3$, the ellipsoid is prolate (cigar-shaped).

One advantage of AMS is that it can be used to study subtle fabrics in a much more efficient manner than measuring mineral orientations in thin section. Magnetic fabric of mafic magmas has been shown to approximate the rock fabric (Ernst and Baragar, 1992). The reason for this correlation is because the distribution of late-crystallizing magnetite follows the pre-existing silicate fabric of the rock formed by the early crystallization of tabular or bladed feldspars (Ernst and Baragar, 1992). This makes AMS useful in the study of petrofabrics. Study of the AMS ellipsoids gives the statistical alignment of platy or elongate magnetic grains (primarily ferromagnetic grains).

AMS is useful in the study of sheet intrusions of mafic composition because the magma will acquire a preferential magnetic fabric. This fabric would show the minimum axis of the AMS ellipsoid aligned perpendicular to the dike/sill wall, and the maximum axis oriented in the direction of flow (Ernst and Baragar, 1992).

Sheet Intrusions: Magma-driven Fractures

Magma confined at depth will try to flow along a path to lower pressures near or at the surface. Sheet intrusions are the end product of magma flowing into and solidifying along dilational fractures. These fractures may form along inherently weak zones already present in the country rock prior to intrusion, e.g. faults, joints, or shear zones, or they may be opened and propagated by the fluid pressure of the magma itself. Fluid pressures originate in magma as a result of density differences between the hot and less dense magma and the cooler and more dense host rock, and/or to boiling of the magma during crystallization processes (Suppe, 1985).

Dilational emplacement of Dikes

For intrusions propagating their own fractures in structurally homogeneous material, intrusion takes place along an intrusion plane that lies perpendicular to the least principal compressive stress (sigma 3), and is parallel to the sigma 1 and sigma 2 plane (Suppe, 1985). For emplacement to occur, magma pressure must be greater than or equal to the tensile strength of the wall rock minus the magnitude of the least compressive stress. Under these conditions, magma pressure acts perpendicular to the intrusion plane of the dike, and the magma effectively wedges apart the host rock. Thus, in regional dike swarms where the host rock is determined to be structurally homogeneous, the orientation of the least compressive stress during emplacement can be determined from the orientation of the dike plane. If, however, previous zones of weakness such as joints, bedding planes, or faults exist in the country rock, then magma will preferentially be emplaced along such zones so long as the magma pressure is greater than the compressive stress acting across the plane of intrusion (Park, 1983).

In some cases an intrusive dike will be represented on the surface by a series of offset but parallel en echelon segments. These segments suggest an intrusive source lying in a plane oblique to the individual segments, but parallel to the zone defined by the segments (Park, 1983)[figure!]. One possibility for the creation of an en echelon pattern of intrusions is that it may represent a change in the orientation of the least compressive stress of a region. When a dike intrudes such a region, it will reorient itself to continue propagating perpendicular to the least compressive stress. This reorientation can be performed by either a tilt or a twist. A tilt occurs by rotation about an axis of tilt that lies in the plane of the fracture surface and parallel to the propagating dike tip. Tilts occur without any physical disruption of the intrusive surface, thereby producing curved dikes. A twist occurs by rotation about an axis of twist that lies in the plane of fracture and perpendicular to the direction of propagation. A twist results in the break-up of the planar surface of the intrusion into a series of discrete en echelon segments (Davis and Reynolds, 1996).

Dilational Emplacement of Sills

A sill is a sheetlike intrusion emplaced parallel to bedding or foliation in the country rock. Emplacement of a sill occurs when magma pressure exceeds the load pressure of overlying strata, and thus sills are usually found in the higher levels of the crust (Park, 1983). A dike may become a sill when the level of emplacement reaches the zone where the least compressive stress becomes oriented vertically (Park, 1983).

Determining Fracture Propagation Direction

Of interest to this study is determining the direction of fracture propagation. One method for making such a determination is to study the geometric features of the intrusion, including structures such as offsets, steps, horns, bridges, and cusps. Descriptions of these features as well as what they reveal about propagation direction of the leading fracture are found below (Figure).

As a dike reorients itself by means of a twist, the plane of the dike is broken into a series of en echelon segments. The direction of main fracture propagation is along the length of the segments. As the intrusion continues to propagate, there is also localized growth in the width and thickness of the individual segments. If the segments are coplanar and continue to grow in width, they will eventually coalesce into a single unit disrupted by **cusps**. Cusps indicate the region where two coplanar segments grew together, and the trend and plunge of cusps indicates the direction of main fracture propagation.

Where individual echelon segments are not coplanar, they are considered offset and different features are created as they grow together. The amount a segment is offset is measured as the distance between segments (separated or overlapping) measured normal to segment strike.

As individual offset segments grow in width, they propagate along their own fracture tips. These tips may propagate along either straight or curved paths depending on the orientation and magnitude of the associated stress fields. (Straight if regional stresses dominate, curved if local stresses are allowed to interact with each other due to weak regional stresses). The extension of these tips, known as **horns**, beyond the terminations of the dike segments, defines local propagation directions within the segment, but lies perpendicular to the propagation direction of the main fracture. (Delaney and Pollard, 1981).

Closely spaced, offset segments that are growing in width may eventually coalesce into a continuous sheet. This is accomplished when the bridge, the volume of host rock found between two converging horns, is first deformed to accommodate dilation of the fractures, and then is finally ruptured and removed (Nicholson and Pollard, 1985). The result of the offset segments linking together is a continuous sheet with **steps** defined by the connecting portion of the dike body that links the dike segments. Local propagation of the segment tips is sub-perpendicular to the steps, whereas the orientation of the long axes of step "corners" defines the propagation direction of the dike plane as a whole.

Formation of the Jurassic Ferrar Dolerite Province, Antarctica

Ferrar Province in Antarctica

(The geology of the Ferrar Province discussed below comes from Tingey, 1991.)

In 1958 Harrington proposed the name Ferrar Dolerites to describe the dolerite sills and dikes intruding the Beacon Supergroup in Victoria Land and George V Land. Intrusive and extrusive equivalents of these dolerites crop out in a roughly linear belt extending 4000km across the continent. Sills are the predominant intrusive type exposed in Antarctica, being best developed in Victoria Land, the central Trans-Antarctic Mountains, the Theron Mountains, and the Whichaway Nunataks. In these areas, the sills have intruded pre-Devonian basement and the overlying sediments of the Beacon Supergroup.

On average, the sills are 150m to 200m thick. Some are up to 400m thick, and the combined thickness of all the sills likely exceeds 1000m. Sills less than 100m thick are characterized by fine-grained chilled margins with coarser cores. Some of the thicker sills appear partly differentiated with zones of pegmatitic dolerite containing lenses and schlieren of granophyre. Ages for the intrusions have been determined by 40Ar/39Ar geochronology at 176.6+/-1.8 Ma (Fleming et al., 1997).

Proposed Models for Formation of the Jurassic Ferrar Province, Antarctica

There are several possibilities regarding the likely magma sources that could have produced the Jurassic Ferrar province intrusions in Antarctica. The first model was proposed by Cox (1988) and can be called the "hot line" model (Figure 5). During the Jurassic there was a zone of subduction acting along the Pacific coast of Gondwanaland. As a result of this subduction, back-arc rifting occurred as tensional forces acted on the Antarctic continent due to subduction suction. If this model proves correct, magma flow directions would be upward along the axis of the linear province, then radially outward in an east to west orientation.

The second model suggests that the magmatism found along the Trans-Antarctic Mountains is associated with Gondwanaland break-up, and had its origin from a plume located near the Karoo province in southern Africa (Figure 6). The model calls for a localized hot spot in this region that would have supplied magma to provinces in South America, Antarctica, and the southern tip of Africa. If correct, the flow indicators in the TAM intrusions should represent approximately unidirectional lateral flow from the Karoo region along the province.

A third proposal for the emplacement of the intrusions along the TAM suggests the possibility of several different intrusion sources located along the extent of the magmatic province (Figure 7). For the purpose of this study, the likely candidates include the Dufek Massif, the Butcher Ridge, and the Warren Range intrusions. Since all date to the Jurassic, it is possible that these three centers, and possibly others, acted concurrently to form the swarm. If this is the case, dikes and magmatic flow indicators should indicate propagation and flow directions radially away from these sources.

References Cited

Baer, G. 1995. Fracture propagation and magma flow in segmented dykes: Field evidence and fabric analysis, Makhtesh Ramon, Israel. In Baer and Heimann (eds), *Physics and Chemistry of Dykes*, 125-138.

Baer, G. and Z. Reches 1987. Flow patterns of magma in dikes, Makhtesh Ramon, Israel. *Geology*, 15: 569-572.

Butler, R.F. 1992. *Paleomagnetism: magnetic domains to geologic terranes*. Boston, Blackwell Scientific Publications: 319p.

Cox, K.G. 1988. The Karoo Province. In J. D. Macdougall (ed), *Continental Flood Basalts*, 239-271.

Elliot, D.H. 1992. In B. C. Storey, T. Alabaster, and R. J. Pankhurst (eds), *Magmatism and the Causes of Continental Break-up*, Geological Society Special Publication No. 68: 165-184.

Ernst, R.E. and W.R.A. Baragar 1992. Evidence from magnetic fabric for the flow pattern of magma in the Mackenzie giant radiating dyke swarm. *Nature*, 356: 511-513.

Fleming, T. H., A. Heimann, K. A. Foland, and D. H. Elliot 1997. 40Ar/39Ar geochronology of Ferrar Dolerite sills from the Transantarctic Mountains, Antarctica: Implications for the age and origin of the Ferrar magmatic province. *GSA Bulletin*, v.109; no.5; 533-546.

Philpotts, A.R. and P.M. Asher 1994. Magmatic flow direction indicators in a giant diabase feeder dike, Connecticut. *Geology*, 22: 363-366.

Smith, R.P. 1987. Dyke emplacement at Spanish Peaks, Colorado. In H. C. Halls and W. F. Fahrig (eds), *Mafic Dyke Swarms*: 47-54. Geological Association of Canada, Special Paper 34.

Suppe, J. 1985. Priciples of Structural Geology. Prentice-Hall, Inc. Englewood Cliff, NJ: 537pp.

Tingey, R. J.(ed.) The Geology of Antarctica. Oxford: Clarendon Press; New York: Oxford University Press, 1991: 680pp.

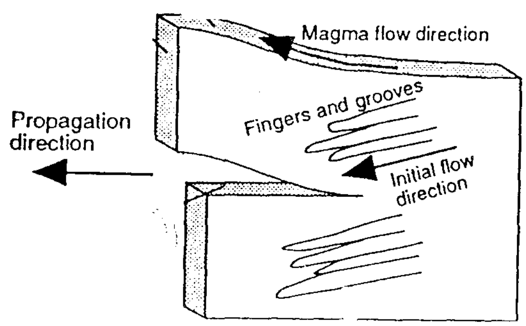
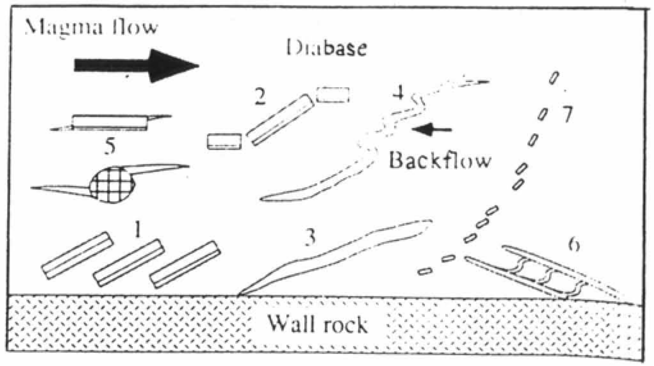


Figure 1: Fingers and Grooves found along dike contact.

(Modified from Baer, 1995)

Figure 2. Flow-direction indicators in margins of Higganum dike: 1—Imbricate phenocrysts; 2—broken and sheared phenocrysts; 3—granophyre wisps emanating from wall rock; 4—granophyre wisps folded by backflow; 5—granophyre segregations attached to phenocrysts; 6—Reidel shears; and 7—ramp structures.



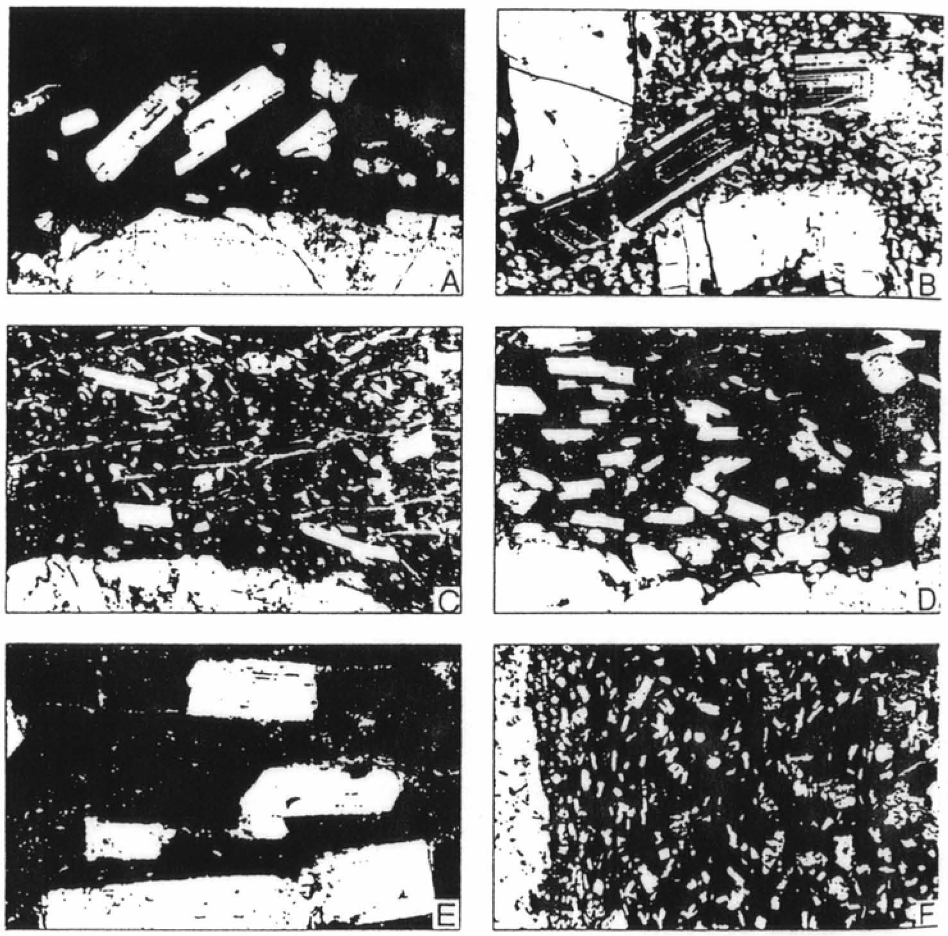


Figure 3. Flow-direction indicators in Higganum dike. Contact is at bottom of photograph and direction of primary magma flow is to right in all but F, where contact is to left and magma flow is upward. All specimens were photographed under transmitted light except B, which was under reflected light. A: Imbrication of plagioclase phenocrysts against wall of dike. Width of field is 2 mm. B: Broken and sheared phenocryst of oscillatory-zoned plagioclase between two orthopyroxene phenocrysts. Width of field is 0.8 mm. C: Wisps of granophyre derived from wall rock streaked out by flow of diabase magma. Width of field is 6.5 mm. D: Early wisps of granophyre that climb from lower left to upper right were folded by backflow of magma (right to left). Width of field is 6.5 mm. E: Granophyre segregations on diagonally opposed corners of plagioclase phenocrysts. Reversed. enlarged image of central left side of D. Width of field is 1.2 mm. F: Ramp structure rising from lower left to upper right is devoid of large phenocrysts. Width of field is 3 cm.

Fig. 2 (Philpotts + Asher 1994)

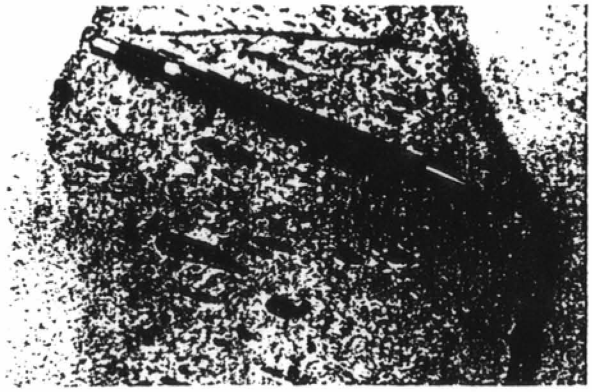


Figure 1. Elongated vesicles in hand sample from Dyke 1.

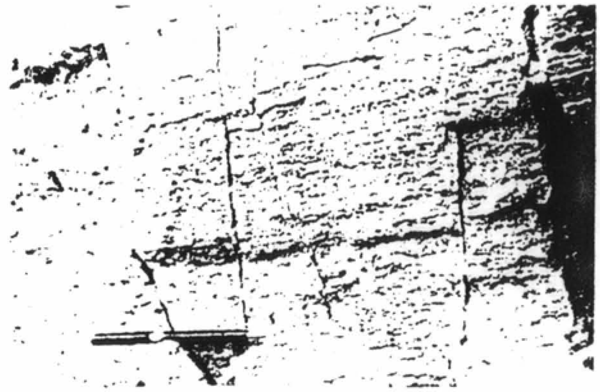


Figure 2. Scour marks in Dyke 22.

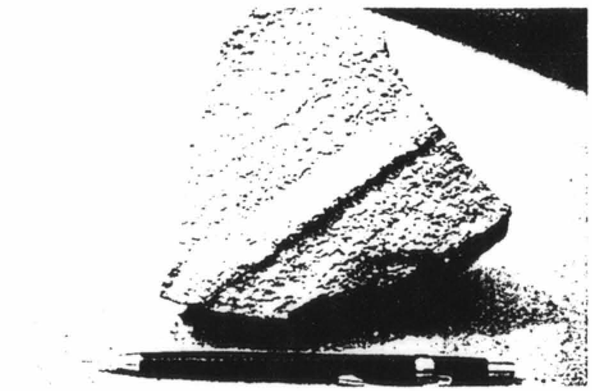


Figure 3. Scour marks in hand sample from Dyke 35.

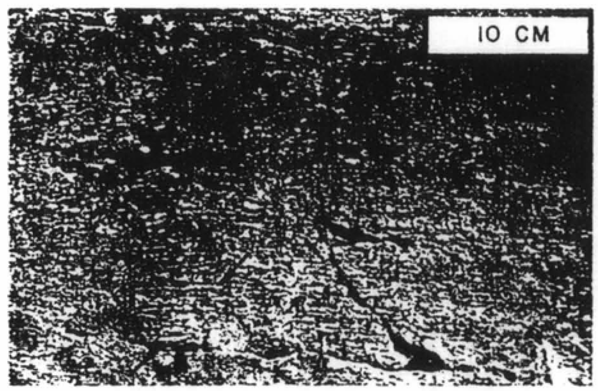


Figure 4. Cataclastically elongated feldspar phenocrysts. Arrows point to individual elongated phenocrysts.

Figure 5. Photomicrograph of catalastically elongated magnetite grain. Plane light.

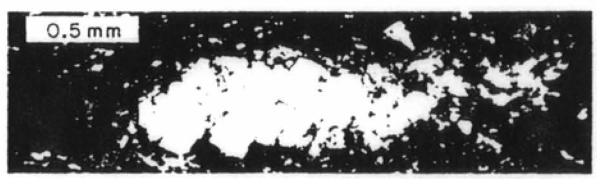


Figure 6. Photomicrograph of cataclastically elongated plagioclase grain. Crossed polars.

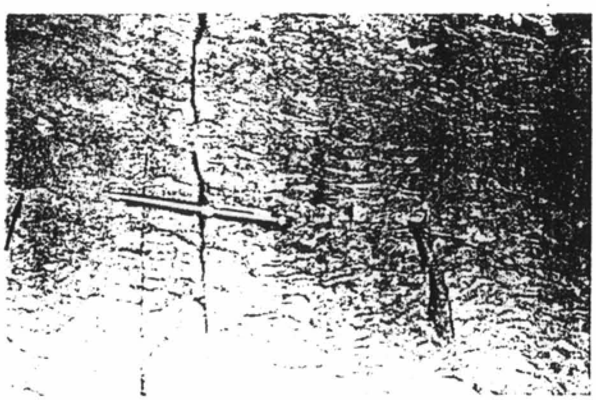


Figure 7. Photograph of folds on contact zone of Dyke 22.

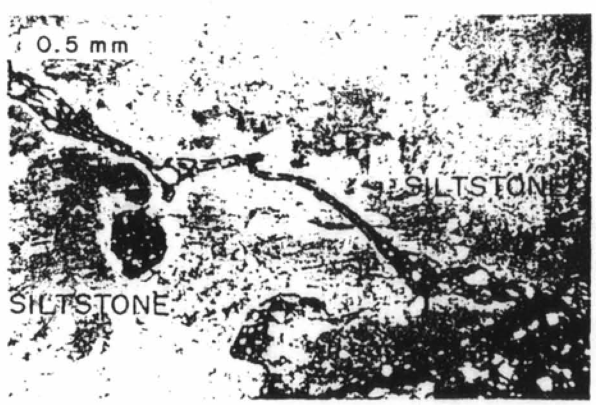


Figure 8. Photomicrograph of an asymmetric fold in cross-section. Siltstone wallrock (light) is buckled into chilled zone (dark). The fold crest has been drawn out in the direction of flow (right to left).

Fig. 3 (Smith, 1987)

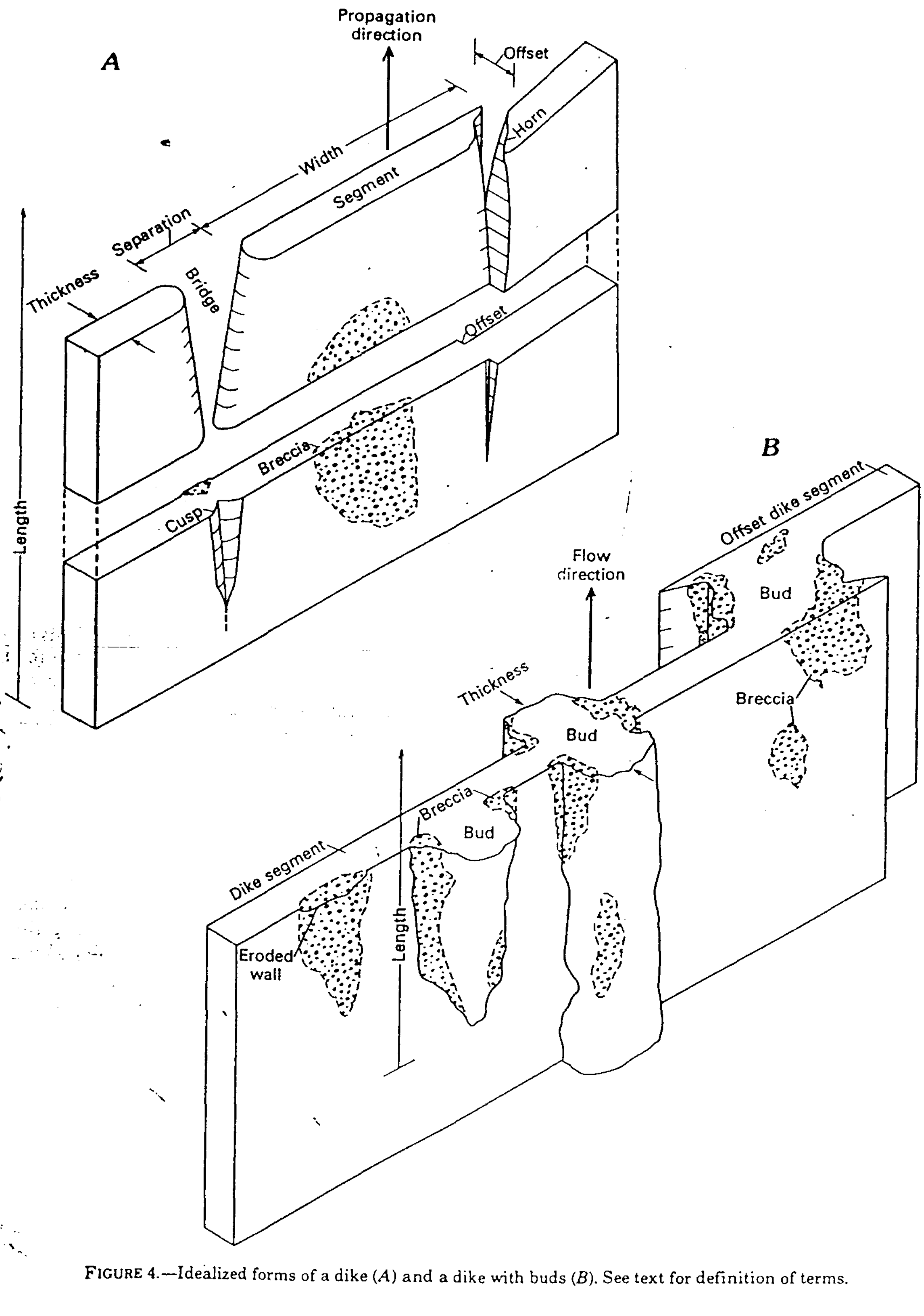


FIGURE 4.—Idealized forms of a dike (*A*) and a dike with buds (*B*). See text for definition of terms.

Fig. 4 (Delaney + Pollard)

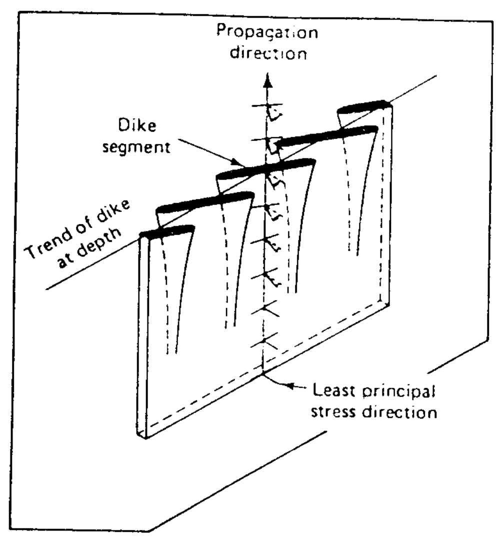


Fig. 5 (Modified from Suppe, 1985)